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Crop management and agronomic context of the Farm Scale Evaluations of genetically modified herbicide-tolerant crops

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The Farm Scale Evaluations of genetically modified herbicide-tolerant crops (GMHT) were conducted in the UK from 2000 to 2002 on beet (sugar and fodder), spring oilseed rape and forage maize. The management of the crops studied is described and compared with current conventional commercial practice. The distribution of field sites adequately represented the areas currently growing these crops, and the sample contained sites operated at a range of management intensities, including low intensity. Herbicide inputs were audited, and the active ingredients used and the rates and the timings of applications compared well with current practice for both GMHT and conventional crops. Inputs on sugar beet were lower than, and inputs on spring oilseed rape and forage maize were consistent with, national averages. Regression analysis of herbicide-application strategies and weed emergence showed that inputs applied by farmers increased with weed densities in beet and forage maize. GMHT crops generally received only one herbicide active ingredient per crop, later and fewer herbicide sprays and less active ingredient (for beet and maize) than the conventional treatments. The audit of inputs found no evidence of bias.

Keywords: sugar beet; spring oilseed rape; maize; weed management; seedbanks; farming intensity

1. INTRODUCTION

Agriculture is the major land use in the UK (Defra 2002*a*) and consequently wildlife and agriculture live closely together (Donald *et al.* 2001). Cropping practices and the management systems operated by farmers directly and indirectly affect weeds, invertebrates and ultimately the mammals and birds that live in or around cultivated fields (Andraesen *et al.* 1996; Gill *et al.* 1996; Chamberlain *et al.* 1999). Declines in numbers of farmland birds (Chamberlain *et al.* 2000) and changes in biodiversity (Robinson & Sutherland 2002) have been attributed to changes in crop management, notably winter cropping, which have been made possible by the use of pesticides and are collectively termed 'increased intensification'.

The main developments in chemical inputs (fertilizers and pesticides) began in the 1960s. Farming in the 1950s was less regionally diversified than it is today, and most farms were mixed and grew crops in addition to keeping livestock. To support the livestock a greater proportion of forage crops were grown than is currently usual on arable farms. Typical rotations had developed from the Norfolk four-course system, which sought to achieve a balance between crops with high nutritional requirements (such as cereals) and crops that left a high nutrient status (such as roots, legumes and short leys). Of the total arable land cultivated in 1950, cereals were grown on 50%, rotational grass and clover on 24% and fodder crops on 9% (Defra 2003). Fodder root crops were replaced by longer leys in the alternate husbandry system or ley farming (Moore 1958), and by 1960 leys covered 30% of the arable land.

In the 1950s the use of hand labour was more prevalent than it is now, and some crops, such as beet, relied on it extensively. Fodder beet (*Beta vulgaris* ssp. *vulgaris*), the product of crosses between mangold and sugar beet (*B. vulgaris* ssp. *vulgaris*) varieties, was a relatively new introduction. It has higher dry-matter content in the root and larger tops than mangold and is suited to machine harvesting. Beet seed (fodder and sugar) was multigerm, each seed giving rise to many seedlings. To obtain a good yield and for ease of harvest, plant stands had to be thinned

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manually (singled) at the four-to-seven-leaf stage (Moore 1958). Hand hoeing was the main method of weed control, although some control was achieved through cultivations such as stale seedbeds (Anon 1955). Hand hoeing was necessary twice before singling and a further three or four times afterwards (Moore 1958). Mechanical thinning alone produced variable plant stands but, when used in conjunction with hand thinning, reduced the time needed for hand singling by 20% (Anon 1955).

Farming practices had to change as workers drifted from the land and hand labour became increasingly expensive and difficult to obtain. In beet, pressure increased for the development of precision drills and the production of monogerm seed. Early trials achieved a satisfactory stand using varieties with 90% single-germ seeds and a precision drill (Anon 1961). These developments reduced the man-hours required for sugar beet production from 310 ha^{-1} in 1954 to 50 ha^{-1} in 1980 (Fream 1983).

The loss of hand labour for singling increased the demand for other methods of weed control. The first post-emergence 'herbicide', sodium nitrate, was found to damage the beet. Early work focused on pre-emergence herbicides (Anon 1957). Herbicides were expensive and, to reduce the cost, the first systems combined sprays as bands over the row with inter-row tractor hoeing.

Trends in weed numbers from the 1950s are hard to find and relatively few studies exist. Records of weed numbers from the 1950s to 1970 on a farm in Norfolk show some species declining while others increased on untreated plots (Bray & Hilton 1975). Total weed numbers during this period on untreated plots showed a slight downward trend but varied greatly year to year from 2–80 m^{-2}. Many of the differences were seasonal and thought to be weather-related, although species composition will change in response to changes in management.

In 1950, some forage maize (*Zea mays*) was grown, but on less than 1% of the arable area (Defra 2003), and McConnell's Agricultural Notebook (Moore 1958) reported that forage maize was suitable for ensiling in areas prone to drought. Forage maize varieties were not widely available for use in the UK until the 1960s and were not taken up by many farmers until the 1980s. By this time, weed control in many crops relied on the use of herbicides. The mainstay of weed control in maize has been and remains the pre- or early post-emergence application of atrazine. Inter-row cultivations were not used because they damaged young plants. Other products used in the 1980s were simazine, cyanazine and mixes containing these substances (MAFF 1982). Grass weeds, where they occurred, could be controlled with incorporated triallate granules. Although it is still used currently, atrazine has an uncertain future and may be banned as a result of the Water Framework Directive (Defra 2002*b*).

Spring oilseed rape (*Brassica napus*) was grown in the 1950s but again only on 1% of the arable area, and it was often a fodder catch crop between other main crops in the rotation. The uptake of rape for oil took off in the 1970s following European Economic Community price support through intervention and the introduction of varieties that were free from harmful impurities (low erucic acid rape), which enabled the meal by-product to be used as animal feed. The area grown increased from 55 000 ha in 1977 to over 170 000 ha in 1982 (MAFF 1983), but the bulk of this (97%) was winter sown (Lockhart & Wiseman 1984). Growing rape offers an opportunity to control grass weeds in cereal rotations, and winter oilseed rape is a useful break crop in winter cereal rotations. Spring oilseed rape is largely grown in areas that have experienced pigeon or disease problems, or where wet weather prevents autumn sowing. Although spring oilseed rape is lower yielding, the timing of operations involved in its cultivation means that it suits some farms better than winter oilseed rape (Lockhart & Wiseman 1984). Weed control in spring oilseed rape is more difficult and expensive than in winter oilseed rape. Out of the 22 products listed in the MAFF booklet for weed control in oilseed rape (MAFF 1983), 12 were suitable for spring crops. The number of products has increased, but recently several have been lost following a European Union review, and once again weed control is difficult. Spring oilseed rape remains less important than winter oilseed rape in England, and in 2000 was grown on 11% of the total English oilseed rape area (M. R. Thomas, personal communication). It is more favoured in Scotland and in the same year was grown on 44% of the oilseed rape area (Kerr & Snowden 2001).

Today, crop production is regionally specialized, and fewer farms are mixed. Fodder beet (*B. vulgaris* ssp. *vulgaris*) and forage maize (*Z. mays*) tend to be found in areas with significant numbers of livestock. Sugar beet (*B. vulgaris* ssp. *vulgaris*) and oilseed rape (*B. napus*) are predominately grown on arable farms. Beet and oilseed rape, and often forage maize, are grown as break crops in cereal-dominated rotations and are grown typically one year in every three, four or five. Beet is never, and oilseed rape is very rarely, grown continuously in England, although forage maize can be.

Herbicide use in crops is well established and conventional herbicides are the main method of weed control. Some degree of weed control can result from the crop rotation used, and other cultural practices, such as stale seedbeds, can reduce weed burdens. Herbicide use in maize and oilseed rape tends to be restricted to one or two applications, frequently pre-emergence. Beet has a more complex herbicide regime, and product mixes are frequently used in programmes. It also remains the main crop for which mechanical weeding is used routinely, largely for the control of weed beet, which cannot be controlled with current herbicide sprays approved for use in beet.

The potential introduction of GMHT crops is considered to be a further change that might increase agricultural intensification (English Nature 1998). Although herbicide use is projected to be lower in GMHT crops (Coyette *et al.* 2002), it is feared that, since the herbicides are more efficient at weed control (Brants & Harms 1998), this may lead to cleaner fields, which may threaten wildlife (English Nature 2000; Royal Society for the Protection of Birds 2003). Many urge the adoption of a precautionary approach to their evaluation (Messéan 2000).

The UK government initiated research into the likely impacts of GMHT crops on farmland wildlife: the FSEs of GMHT crops (Firbank *et al.* 1999). The FSEs were designed to test the null hypothesis that there was no difference between the management of GMHT varieties and that of comparable conventional varieties in their effects on wildlife abundance and diversity. The FSEs began in spring 1999 with a pilot year for protocol development. Crops studied in the FSEs were beet (fodder and sugar), forage maize and winter and spring oilseed rape. Although it was studied in the FSEs, the final harvest of winter oilseed rape is due in summer 2003 and the results will be reported later. Each of the three spring-sown crops in the FSEs was regarded as a single experiment and was studied in 2000, 2001 and 2002 (Firbank *et al.* 2003), with a target of between 60 and 70 sites to ensure sufficient statistical power (Perry *et al.* 2003).

These GMHT crops were included in the FSEs because they had already been assessed as safe in terms of human health and direct environmental impacts. As GMHT crops, they had obtained regulatory approval for commercial cropping in the UK (maize) or were in the final stages of the approval process (sugar, fodder beet and spring oilseed rape). They cannot be grown commercially without a national seeds listing, approval for pesticide application and the removal of the industry voluntary moratorium.

This paper outlines the site-selection process, and the results of the selection are presented in electronic Appendix A, available on The Royal Society's Publications Web site. Management of the GMHT crops in this study is compared with contemporary practice, and the pesticides-audit process is described. Relationships between weediness, inputs and farmer behaviour are investigated. This paper sets the context for the evaluations of plant and invertebrate indicator species presented in subsequent related papers (Brooks *et al.* 2003; Haughton *et al.* 2003; Hawes *et al.* 2003; Heard *et al.* 2003*a*,*b*; Roy *et al.* 2003).

2. METHODS

(a) *Operation of FSE sites*

Sites were selected to represent the range of agricultural and environmental conditions likely to be encountered during any large-scale cropping; another criterion for site selection was their adherence to the conditions of the experimental release consent of the GMHT varieties (Firbank *et al.* 2003). A questionnaire was sent by the research scientists to volunteer farmers in each year asking for details of their farm and farming practices and the potential diversity of their site. This information was used as the basis for site selection. Provided that the farmers selected by the research scientists could meet the conditions of the release consent, contracts were signed between the farmer and SCIMAC to grow crops as sites for the FSEs. From the pool of offered sites, 66 beet (40 sugar, 26 fodder), 68 maize and 67 spring oilseed rape sites were selected and sown for the FSEs. Once field sites were agreed, subsequent division of fields and allocation of treatments were conducted by the research scientists (Perry *et al.* 2003).

The contracted farmers were supplied with information from SCIMAC on growing the crops, including the *Code of practice on the introduction of genetically modified crops* and *Guidelines for growing newly developed herbicide tolerant crops* (SCIMAC 2002*a*,*b*). The Code covers the supply of information and the record-keeping necessary for growing GMHT crops, and the Guidelines summarize good agricultural practice, such as control of volunteers, separation distances and harvest procedures.

Farmers growing GMHT crops also had to comply with the relevant release consent conditions. In beet, one of the release conditions was the prevention of pollen release; crops were monitored at frequent intervals by SCIMAC staff and all flower stems removed. The GMHT crops remained the property of SCIMAC and the farmers acted under their guidance regarding the release consent, including crop disposal. All GMHT crops produced on these sites were removed from the human and animal food chains. Maize was chopped and buried on the producing farm. In beet and spring oilseed rape, the roots and seeds, respectively, were buried in landfill. For sugar beet the processor, British Sugar, developed an audit trail to prevent the accidental introduction of GMHT roots into the sugar-processing factories. In a substantial deviation from commercial practice, the GMHT sugar beet and much of the GMHT fodder beet were harvested in August and September of each year, earlier than normal and before the sugar-processing factories opened. The conventional beet at these sites was harvested at the normal time. The possible implications of this early harvest on weed-seed return are covered in Heard *et al.* (2003*a*).

(b) *Selection criteria*

The issue of representativeness was addressed by attempting to select fields that encompassed the full range of variation, in various variables, that is likely to be found in commercial practice with regard to geographical distribution, usual agronomy, soil types and field sizes. The approach in the FSEs was not to sample farms in strict proportion to their frequency of occurrence according to any single factor, but rather to ensure adequate representation of the less intensive and more biodiverse situations. Particular attention was given to the geographical range and the variation in intensity of farm management. Although continuous maize is not grown on a large area in the UK, such sites were given high priority because they offered the only opportunity to study any cumulative effects of GMHT cropping (Firbank *et al.* 2003; Perry *et al.* 2003).

Field sizes were intended, as far as possible, to reflect the range used commercially. The regulatory consents governing the FSEs required beet roots and spring oilseed rape seeds to be disposed of by burial in deep landfill sites. Since yields are 27 times greater in sugar beet and 40 times greater in fodder beet than in oilseed rape, it was not possible to grow GMHT beet on large areas owing to the high cost of crop disposal.

Since the farmer was unlikely to have direct information on the diversity of wildlife on the farm, this was estimated indirectly using several different measures. The first was based on an arbitrary weighted score of the environment-enhancing measures that the farmer had undertaken on the farm (Firbank *et al.* 2003). The system allocated a score of two if the farmer had undertaken a Linking Environment And Farming audit (Drummond & Purslow 1997) or had consulted a Farming and Wildlife Advisory Group adviser. A score of one was allocated if wildflower strips, conservation headlands or beetle banks were included around fields and 0.5 if the farm was managed for game or grew game cover crops. The scoring system was additive for all measures undertaken on the farm and possible scores ranged from zero, no measures, to eight, all possible measures had been adopted on the farm.

Cropping intensity was another surrogate for diversity and was compared using cropping-intensity scores and the farm-average winter wheat yield. Cropping-intensity scores were allocated by self-assessment, and farmers were asked to assess the intensity of their production system on a scale ranging from zero (low) to five (high). The farm-average winter wheat yield was a less subjective means of comparing farms and was requested from beet and spring oilseed rape farmers. Where wheat was not grown, an extrapolation was made from the yields of other winter cereals on that holding.

Low-intensity farms are relatively rare, but they may contribute proportionately more to biodiversity than intensively managed farms (Watkinson *et al.* 2000). The selection process sought to favour sites that were managed less intensively, based on these three measures (environmental management measures, intensity score and wheat yield), as these sites might be most affected by the use of more efficient herbicides. Fodder beet was over-sampled in relation to its contribution to the national beet crop (nationally, fodder beet accounts for 6% of the area occupied by sugar beet) for the same reason.

(c) *Seedbank sampling*

Since no data were available on the baseline level of diversity found on each site, soil seedbank samples were used as indicators of the likely densities of weeds and the range of weed species present on the sites before the crops were sown (Squire *et al.* 2003). Samples of soil were taken and estimates of seedbank densities determined following the germination method described in Heard *et al.* (2003*a*). Baseline weed seedbank densities were compared against the environmental-management measures, intensity scores and winter wheat yields provided in the questionnaires to assess the success of using these indicators in the selection process.

(d) *Crop management*

Decisions on crop management were taken by the farmers to simulate the situation that would occur if these crops were grown commercially (Firbank *et al.* 2003; Perry *et al.* 2003). General information on the way the studied crops are usually grown in the UK is supplied in table 4 of electronic Appendix A. Crop-management details were collected during the season, and the research scientists monitored inputs. In addition, growers were required to inform the research scientists immediately when herbicide applications were made so that the appropriate assessments could proceed.

The management of the conventionally grown crops followed the farmers' normal practices and they used their usual advice channels or adviser. By contrast, farmers and their advisers were unfamiliar with growing GMHT crops, especially in the first year of participation in the FSEs. Although some information was provided to them in the form of simulated product labels, SCIMAC had a necessary role in providing advice on herbicide applications to farmers and their advisers, for the GMHT crops only. This information cascade was similar to the normal procedure for the introduction of a new product or technology. For both crop types, the farmers were asked to use levels of inputs that were cost-effective.

The research scientists instituted internal checking processes for all aspects of crop management, of both conventional and GMHT crops, and an audit of inputs was conducted by British Agrochemical Supply Industry Scheme registered individuals. Inputs were compared with label recommendations for conventional herbicides and other pesticides, and with the simulated-label recommendations for the herbicides in GMHT crops. These inputs (doses and timings) were compared with data collected by the research scientists on crop and weed growth stage and ground cover. At each site visit, provided that it was more than 14 days after the previous visit, the growth of the crop (conventional and GMHT) was assessed 4 m and 32 m from the edge of the field on transects 2, 6 and 11 (for site layout, see Heard *et al.* (2003*a*)). Assessments at each location recorded crop height (cm) and percentage cover for the crop and total vegetation. Weed cover was estimated by subtraction. These data were used as part of the audit process to compare weed and crop growth with herbicide applications. Growers agreed to keep all advice notes and details of pesticide applications and hold them open to scrutiny by the research scientists at any period during and immediately after the experiment.

A total of 201 FSE sites were sown with the spring crops, and data were collected from the farmers for all inputs applied to both the conventional and the GMHT crops at each site.

(e) *The GMHT crops*

The GMHT beet crops in the FSEs were tolerant to glyphosate (Roundup Biactive 360 g AI l^{-1}), which gives post-emergence broad-spectrum control of annual and perennial broadleaved and grass weeds (Firbank 2003). The sugar beet cultivar, Sturgeon, is diploid and in NIAB official tests gave a higher yield than the conventional control varieties. The fodder beet, Simplex, is a diploid light-yellow hybrid with a dry-matter content between those of the commercial conventional varieties Kyros and Magnum. These NIAB trials showed that the varieties were stable both under conventional management and when treated with Roundup Biactive. Roundup Biactive is systemic and has no residual activity on weeds in the soil and relatively little activity on invertebrates. Application of herbicides to the crops in the FSEs was allowed through an AEA granted by the PSD. The studies were carried out using a simulated label in the form of a written advisory leaflet, which recommended maximum rates and timings for applications. The maximum total rate permitted was 6 l ha^{-1}. The latest recommended crop growth stage for applications in the draft label was 60–70% canopy closure. The latest legally approved timing of application under the AEA was three weeks before harvest.

The GMHT maize and spring oilseed rape cultivars used in the FSEs were tolerant to glufosinate-ammonium (Liberty, 200 g AI ha^{-1}), which gives post-emergence broad-spectrum control of annual grasses and broadleaved weeds (Firbank 2003). The maize cultivar, Chardon LL, is described as a medium early cultivar (similar to Symphony/Helix) suited to good maize-growing areas. The spring oilseed rape cultivars were PH96S-452 and AVSH1. Both of these cultivars are fully restored F_1 hybrids and are suited to all areas of the UK. PH96S-452 has completed NL trials and is currently awaiting proposal to the NL. AVSH1 is not in NL trials. Yields derived in NL trials use the GMHT cultivar but treat it with conventional herbicides. Glufosinate-ammonium works by contact action after uptake by the leaves and aerial parts of the plant, and some limited local movement can occur in the plant. Under the conditions of the simulated product label, the recommended maximum individual rate was 4 l ha^{-1}, depending on the weeds present and their growth stage. The maximum total rate permitted was 8 l ha^{-1}. Application was permitted until the nine-leaf stage in maize or until the flower buds were visible in spring oilseed rape.

(f) *Statistical analysis*

Confidence intervals (95%) were calculated for the distribution, per crop, of sites used in the FSEs assuming a multinomial distribution with probabilities derived from the observed frequencies within each region, totalled over years. Multiple linear regression was used to establish the relationship between the baseline seedbank densities and some of the site-selection criteria (environmental-management measures, cropping-intensity score and winter wheat yield). The choice of herbicide active ingredient was compared with the national published figures using Spearman's rank correlation.

Herbicide use in the FSE conventional crops was compared with that in the FSE GMHT crops using a standard randomized block ANOVA with the n sites as blocks. The data were the number of sprays, the number of AIs or the total amount of AI (g AI ha^{-1}).

The basic analysis used in the FSEs was a randomized block ANOVA of transformed values, termed the lognormal model by Perry *et al.* (2003). The treatment effect was measured as R, the multiplicative ratio of the GMHT treatment divided by the conventional treatment (see Heard *et al.* 2003*a*). To test the possible effect of a late application of herbicide on these analyses, a covariate analysis was done for various of the weed-response variables reported by Heard *et al.* (2003*a*). The covariate factor, formed for each half-field, indicated whether the herbicide application was within label recommendation, based on the estimated (from FSE crop assessments) crop growth stage at application.

Three herbicide strategies adopted by farmers were identified and tested for evidence of responsiveness to the emerging weed burden. Herbicide use, as both the number of herbicide applications and the amount of AI applied, was regressed against weediness, expressed as pre-herbicide seedling counts (Heard *et al.* 2003*a*) for each of the strategies using multiple linear regression with groups.

(g) *Foot and mouth disease*

In 2001, some farms were affected directly, through infection, or indirectly, through movement restrictions, by foot and mouth disease. Since the beginning of the FSEs, a hygiene protocol was followed to guard against the accidental spread by staff on the project of the beet disease rhizomania. As soon as the foot and mouth outbreak occurred, this protocol was rewritten to include precautions to protect farms against the inadvertent spread of this disease by research staff, and this was followed until the end of the outbreak in early 2002. The rhizomania precautions remained in place. In some cases, access to certain farms was restricted. Foot and mouth disease affected seven farms and resulted in 20 missed protocols (for example, a protocol could be a seedling count or a gastropod search), with delays to some others. Affected sites continued to grow the crop and monitoring recommenced once permitted. Data depending on missing assessments were removed from the analyses. A similar process was used for other data missing as a result of accidental damage or vandalism.

3. RESULTS

(a) *Site selection*

(i) *Geographical distribution, soil type and field size*

The distribution of field sites, by Government Office Region, was compared with the Defra June census data (see table 5*a–d* in electronic Appendix A). It generally reflected very well the areas that grew these crops nationally. For beet, the deliberate use of a disproportionately large number of fodder beet sites, chosen because they are generally of low intensity, increased the percentage of total beet sites in the Southwest. For forage maize, although somewhat fewer sites were offered in the Southwest than was typical, the achieved replication of 12 sites, together with 16 in the Midlands and West, was adequate to detect any interaction between treatment and environment, should any have occurred. Similarly, the small number of sites for spring oilseed rape in the Southeast was offset by larger numbers in the neighbouring Eastern region.

Although it was not used as a factor in the site-selection process, texture was determined from the soil samples taken for seedbank analysis (see table 6 in electronic Appendix A). Beet was frequently grown on the lighter soils (60% on sandy loam and loamy sand); maize was grown across a wide range of soil types with large numbers on sandy loam and clay loams, and spring oilseed rape was more often grown on heavier soils such as silty clay and clay loam.

A variety of field sizes were sought, and maize fields were the smallest with most measuring less than 10 ha (see table 7 in electronic Appendix A). Beet and spring oilseed rape fields were larger and generally measured up to 15 ha. Owing to the high cost of disposal, many of the GMHT beet sites monitored were 2 ha, which was compared with an equivalent area on the adjacent conventional beet crop, with assessment areas focused on the natural margins.

(ii) *Environmental management, intensity scores and winter wheat yields*

Environmental-management scores ranged from a maximum of eight at one site to zero at 30% of the sites (see table 8*a* in electronic Appendix A). Half of the sites for each crop scored between zero and two. Most farmers scored their cropping intensity in the middle-to-high side of the range, with scores of three and four (see table 8*b* in electronic Appendix A). Similarly, for beet and spring oilseed rape, winter wheat yields were frequently average to high; the national average is 8 tonnes ha^{-1}. At approximately two-thirds of sites, wheat yields were 8–10 tonnes ha^{-1} (see table 8*c* in electronic Appendix A), and *ca.* 20% of sites quoted yields of 6–8 tonnes ha^{-1}.

(iii) *Seedbank samples*

Baseline seedbank samples for the FSE sites contained a wide range both of seed densities (figure 1*a*) and of numbers of species (figure 1*b*). The distributions of densities and species numbers between crops were very similar and have been considered as single distributions. Both had nearly symmetric unimodal distributions. The range of seedbank densities found in the FSE baseline samples was compared with historic seedbank data from before and after the widespread introduction of herbicides in the 1960s (Squire *et al.* 2003). The FSE baseline and post-1960s distributions both ranged over two orders of magnitude and had a mode of about 2500 seeds m^{-2} (figure 1*a*).

To assess the success of the criteria used in site selection in identifying sites of different diversities, seedbank densities were regressed against environmental-management measures, cropping-intensity scores and winter wheat yields (see electronic Appendix A, figure 7*a–c*). Environmental-management measures ($p = 0.659$) and winter wheat yields ($p = 0.471$) were not related to baseline seedbank densities. However, despite wide scatter, the relationship between cropping intensity, as estimated by the farmer, and seedbank density ($p = 0.001$) was significant. Sites that were farmed less intensively had high seedbanks and, conversely, only sites farmed intensively had

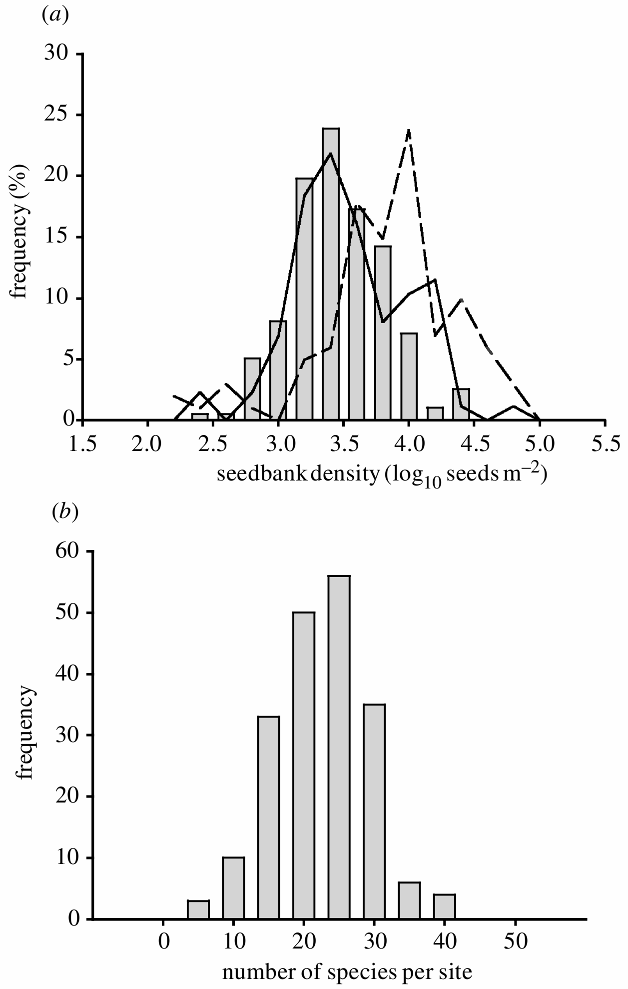

Figure 1. (*a*) Baseline weed seedbank densities from the FSE spring crop sites 2000–2002 (histogram), $n = 197$, overlaid with the distributions of soil seedbank densities from samples taken pre-1960 (dashed line) and post-1960 (solid line) from Squire *et al.* (2003). (*b*) Baseline weed seedbank number of species per site from FSE spring crop sites 2000–2002, $n = 197$.

low seedbanks; however, some intensively managed sites were also very weedy.

(b) *Crop management*

(i) *Sowing dates and crop cultivars*

Sowing dates are presented as cumulative percentages of the total area sown (see electronic Appendix A, figure 8*a*–*d*). These are compared with other data sources where available. Sugar beet was sown in mid-March to mid-April, and the sowing dates for conventional sugar beet FSE sites varied greatly with year. Being later-sown crops, fodder beet (April–May) and forage maize (May) were less affected by year. Generally, slight delays were seen in 2000 and 2001, but 2002 closely fitted the national trend. Spring oilseed rape was sown from March to May. The extended sowing period may be a consequence of re-drilling, since it is fairly common for a few spring oilseed rape crops to fail in most years; this happened for a few sites in the FSEs.

Sowing dates of conventional and GMHT crops at each site were the same on *ca.* 80% of occasions. Where differences in sowing dates occurred, these were small and either crop could be the one sown later. The largest differences occurred on spring oilseed rape sites, where, on three sites, although originally sown on the same date, one or other half of the field failed and had to be re-drilled. This occurred twice for the GMHT and once for the conventional oilseed rape, resulting in differences of 20–39 days between halves. On two sites, both spring oilseed rape crops failed and both were re-drilled on the same date. The re-drilling of sites was considered to be normal practice, and re-drilled sites remained in the study.

The most common conventional cultivars used in the FSEs are listed in table 9 of electronic Appendix A. Cultivars for the GMHT crop were those specified in the release consents.

(ii) *Timing of herbicide applications*

For cost-effective weed control, the timing of applications should depend on the number and species of weeds present and the growth stages of the crop and weed. These factors are greatly affected by the date of sowing. Crop growth (ground cover or height) and weed cover, both derived from the crop assessments, were compared with the timing of herbicide applications expressed as the number of days from sowing grouped in two-week intervals (figure 2*a*–*c*). The herbicide applications are drawn as box-and-whisker plots. At the latest timings only a few data points may exist, and only the box is drawn.

In beet (figure 2*a*), up to six herbicide applications were made in the conventional crop, compared with one or two in the GMHT crop. Mean timings for the first herbicide application were 15 days after sowing for conventional beet and 49 days after sowing for GMHT beet, but many conventional beet sites were treated pre-emergence (45%). Weed cover on the GMHT plots developed more quickly than on the conventional plots. The median and range of the weed cover are greater on the GMHT plots than on the conventional ones and are greatest between 43 and 70 days after sowing. Crop development in beet was expressed as crop cover, and this developed rapidly between 30 and 100 days after sowing, when it reached a maximum of *ca.* 80% cover. There was little difference in development between the GMHT and conventional cultivars.

Pre-emergence herbicides were applied to similar proportions of maize sites (47%) as beet sites (figure 2*b*). Average timings for the first herbicide application were 22 days after sowing for conventional and 38 days after sowing for GMHT maize. Second conventional herbicides were applied on only 22% of sites and over a relatively short period of time. Second applications of GMHT herbicide occurred on 19% of sites but over a longer period than for conventional herbicides. Weed-cover development was similar to that in beet: with the later commencement of GMHT applications, greater weed cover developed in GMHT than in conventional maize. Overall, weed cover was greater and more variable between sites in maize than in beet. Crop development in maize, described by crop height, reached a maximum at *ca.* 100 days after sowing. There was little difference in development between the conventional and GMHT cultivars.

In spring oilseed rape (figure 2*c*), pre-emergence herbicide was applied to 47% of sites, and 35% of sites received trifluralin. Herbicide was applied to conventional crops

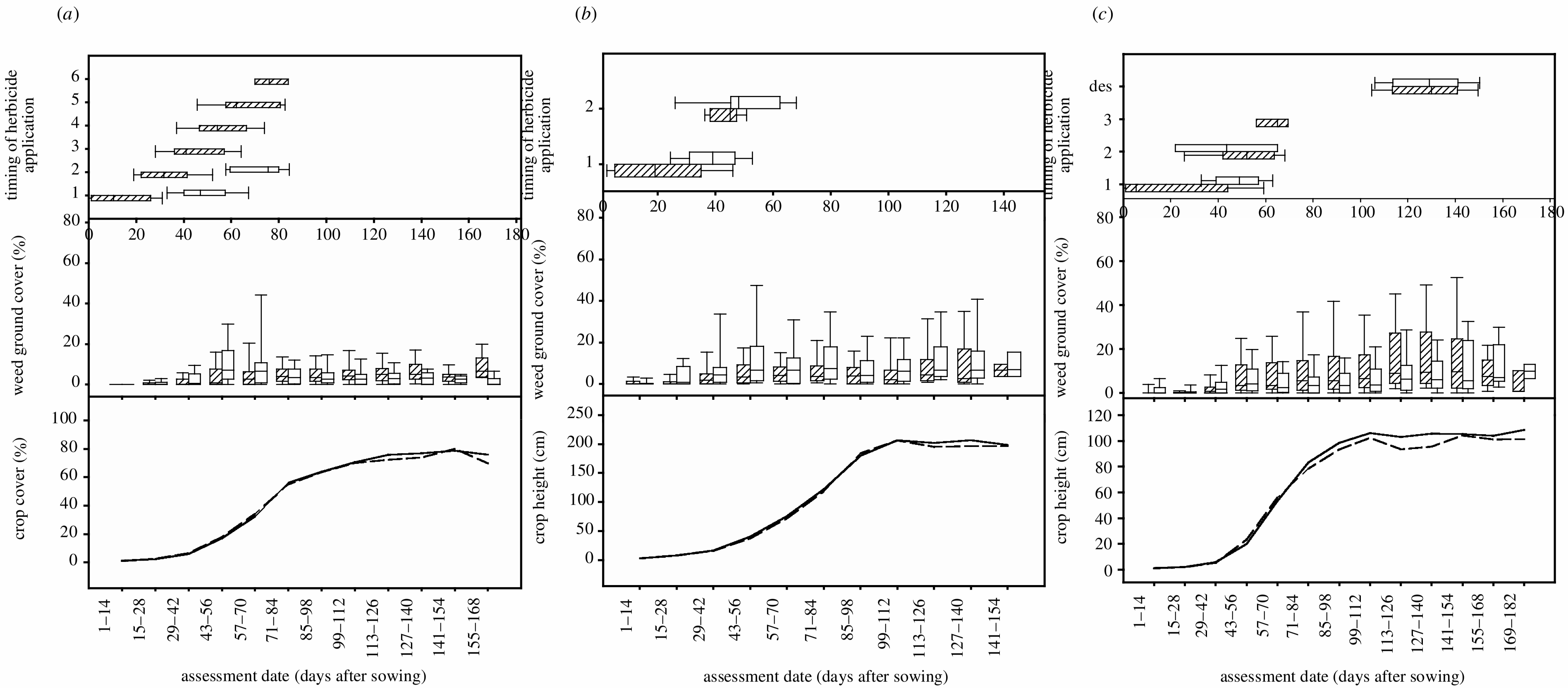

Figure 2. Timing of herbicide applications relative to weed and crop growth in (*a*) beet, (*b*) maize and (*c*) spring oilseed rape. Timing of herbicide applications (top), percentage weed cover (middle) and percentage crop cover (for beet) or crop height (for maize and spring oilseed rape) (bottom) against the number of days from sowing for conventional (hatched boxes, dashed lines) and GMHT (open boxes, solid lines) crops. Boxes denote the 25th and 75th percentiles, and a line indicates the median; whiskers denote the 10th and 90th percentiles. (*a*) Herbicides applied to conventional 1–6 ($n = 66$, 60, 47, 26, 9 and 4, respectively) and to GMHT 1–2 ($n = 64$ and 24, respectively). (*b*) Herbicides applied to conventional 1–2 ($n = 65$ and 17, respectively) and to GMHT 1–2 ($n = 64$ and 15, respectively). (*c*) Herbicides and desiccants (des) applied to conventional 1–3 and des ($n = 56$, 17, 3 and 41, respectively) and to GMHT 1–2 and des ($n = 62$, 1 and 41, respectively).

once on most sites; however, some sites were not treated at all, on the conventional side alone (6 out of 67), the GMHT side alone (2 out of 67) or both (3 out of 67). Three sites were treated three times and one site was treated four times. GMHT herbicides were generally applied once. Desiccants were also applied to the spring oilseed rape crops and are included for comparison with crop development. The timing of desiccant application was similar for conventional and GMHT cultivars. In contrast to beet and maize, in spring oilseed rape weed cover developed more rapidly on the conventional plots owing to poor control. Both the mean weed cover and the range between sites were larger on the conventional than on the GMHT crops, except at the penultimate assessment. As in the other crops, maximum crop development (height) was attained *ca.* 100 days after sowing. Some small variations in height after this time may indicate the effects of lodging. Small differences in average height were recorded between the conventional and the GMHT cultivars.

(iii) *Timing of the first herbicide applications*

The herbicide use in all conventional crops was dominated by the pre-emergence herbicides, as seen in figure 2. Timings to first herbicide application are plotted as frequency distributions in figure 3*a–c*. Approximately 50% of all sites for each crop received a conventional herbicide spray within the first 14 days after sowing. For GMHT crops, the number of sprays applied peaked at 36–42 days in beet (figure 3*a*) and maize (figure 3*b*) and at 50–56 days in spring oilseed rape (figure 3*c*).

(iv) *Herbicide use*

The PSD surveys national pesticide inputs on certain crops, in certain years. In England, the latest data were published in 1999 and covered grassland and forage crops grown in 1997 (Garthwaite *et al.* 1999) and arable crops grown in 1998 (Garthwaite & Thomas 1999). A more recent pesticide-use survey was conducted in 2000 and, although not yet published, the data on inputs in sugar beet and spring oilseed rape are included in this paper (M. R. Thomas, personal communication). Scottish data on pesticide use were produced by the Scottish Agricultural Science Agency in 2001 based on surveys undertaken in 2000 (Kerr & Snowden 2001), and some are included for comparison with the English data. To enable a comparison to be made between inputs on the FSEs and national average pesticide data it was necessary to separate the beet crops. Sugar beet is part of the survey of arable crops (1998 and 2000) and fodder beet is surveyed as a forage crop (1997). For analyses not reliant on these data, beet was treated as one crop.

Owing to the importance of the herbicide input data, it will be compared in detail with national figures for AIs used, the percentage of fields treated, the number of sprays, the number of AIs and the amount of AI used. The most frequently used herbicide AIs, from the national pesticide surveys, are presented in table 1 as percentages of the total area treated with herbicides. Similar figures are calculated for the FSEs as the number of sites treated with an AI relative to the total number of sites. The use of herbicide AIs in each crop matched those of the national survey on the basis of Spearman's rank correlation ($p = 0.001–0.049$).

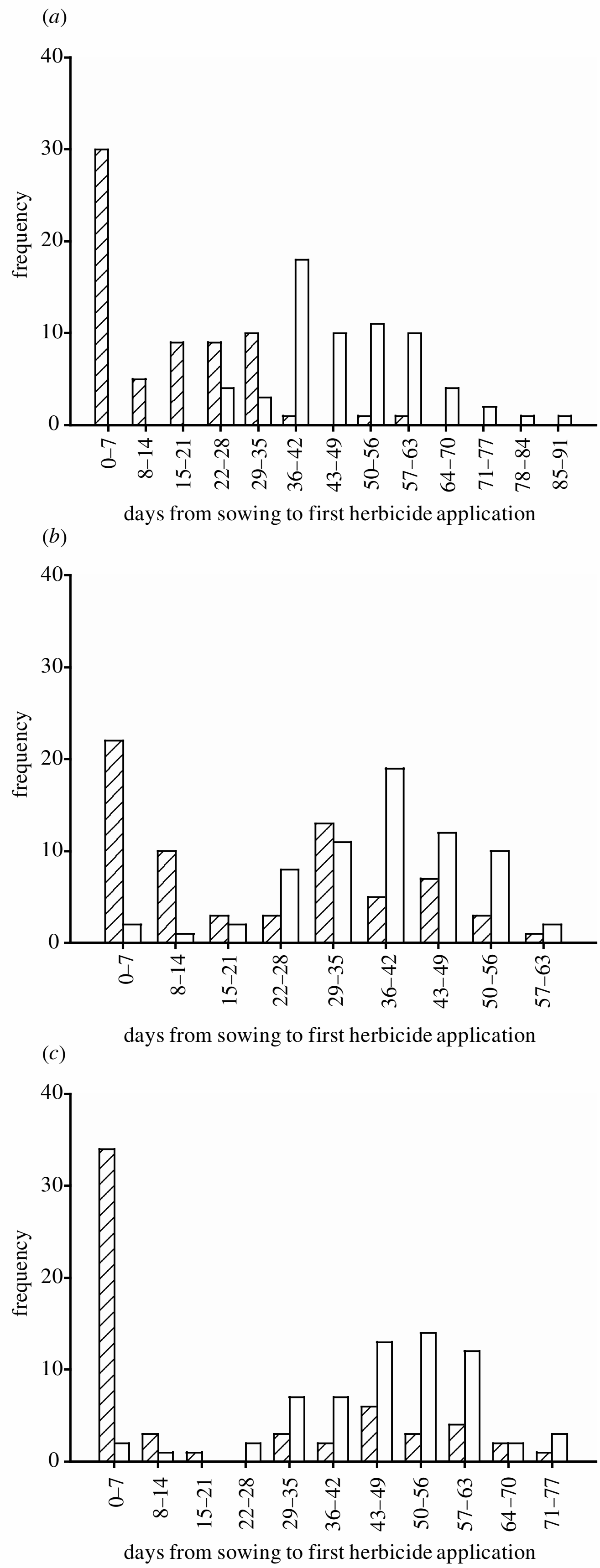

Figure 3. Intervals between sowing and first herbicide application in (*a*) beet, (*b*) maize and (*c*) spring oilseed rape. Frequency distributions of the interval (days) between sowing and application of first herbicides in conventional (hatched boxes) and GMHT (open boxes) crops.

With a few exceptions, the amount of herbicide used was similar in the FSEs to national data (table 2). The percentage of spring oilseed rape fields untreated with herbicides was lower in FSE conventional crops (6%) than nationally (21%) in 2000. However, in 1998, 4.4% of fields of oilseed rape did not receive herbicide (Garthwaite & Thomas 1999), suggesting wide yearly variation. The percentages of untreated conventional and GMHT fields in the FSEs were not significantly different from national figures in any of the crops.

The number of conventional herbicide sprays was slightly higher in FSE fodder beet and spring oilseed rape and slightly lower in sugar beet and maize than the national averages. The numbers of sprays of GMHT crops were significantly lower in fodder beet, sugar beet and spring oilseed rape than in their conventional equivalents; the numbers of sprays in GMHT and conventional maize were not significantly different. Similarly, the numbers of AIs applied to conventional fodder beet and spring oilseed rape were slightly greater, not different for maize and less for sugar beet than the national averages. All GMHT crops received significantly fewer AIs than the conventional equivalents.

The amount of AI applied was similar to that in the national survey. For the purposes of comparison with the national-survey data, these figures include the use of predrilling treatments and, in addition, for spring oilseed rape the figures include desiccant AIs (which are not applied to beet and maize). The FSE conventional sites show wide ranges in the amount of herbicide applied, and the survey means for fodder beet and maize are within one standard error of the FSE conventional means. Quantities of AI used on the GMHT crops were significantly lower than on the conventional crops for beet and maize, by *ca.* 50%. In spring oilseed rape, a low-input crop, the use of AI did not differ significantly between GMHT and conventional crops. The AI used in spring oilseed rape was *ca.* 50% of the amount used in beet and 80% of that in maize.

(v) *Insecticide, fungicide, molluscicide and nematicide use*

Within the FSEs, only herbicide use varied routinely between the GMHT and conventional crops. Other inputs were usually the same, unless treatment was required on only one half for agronomic reasons. The most frequent such situation was the use of fungicides in beet crops to protect against powdery mildew (*Erysiphe betae*). This disease appears in late July and August and, in normal years, fungicide is not applied to early-harvested crops. On the FSE sites, the GMHT beet was harvested early, in August and September. At five beet sites, only the conventional crop was treated with fungicide and early harvest was given as the reason for non-treatment of the GMHT crop.

Imidacloprid seed treatment was applied only to sugar beet and was used on 70% of conventional and 65% of GMHT sites. On an additional 7% and 5%, respectively, of the sites of conventional and GMHT sugar beet the seed was treated with tefluthrin. Many maize sites were sown with seed treated with mesurol and some spring oilseed rape seed was treated with gamma-HCH.

Although there were some variations, there was reasonable agreement between the FSE data and national figures in most cases for insecticides, fungicides and molluscicides (table 3). Insecticide–nematicide use was nearly 50% higher than the national average in beet owing to the relatively frequent use of aldicarb granules against nematodes: 7 out of 40 sites (18%) compared with 6–10% nationally. Molluscicide use was also higher on the FSE sites than in the national survey but treatments were applied to both sides of each site. Insecticides were used on 76% of FSE spring oilseed rape sites in 2000–2002, compared with 54% of fields nationally in 2000. In contrast, fungicide was applied to fewer FSE fields in spring oilseed rape than the national average, although, where used, rates of AI were similar. Fungicide use on FSE sites was similar to the national figures for the other crops, and molluscicide use was broadly similar for all crops.

(c) *The audit of crop management*

The audit of crop management confirmed that, in the vast majority of cases, crop management was appropriate and in agreement with current commercial practice. However, it also highlighted a small number of practices followed by farmers that were unusual.

In conventional beet, label recommendations were not adhered to at two sites. In one case, the maximum number of applications for one product was exceeded and in another the recommended interval between sprays was not met. Not all products used had full approval, such as desmedipham (as in Betanal Compact) in conventional fodder beet, but this use is allowed under the long-term arrangements for the extension of use in minor crops.

Applications of glyphosate (Roundup Biactive) to the GMHT beet were also somewhat variable. The latest timing of application given in the simulated product label was canopy closure, but the experimental permit allowed treatment up to three weeks before harvest. In some cases, applications were made later than the draft-product-label recommendation (borderline on one site, late on three sites), but none contravened the experimental permit so all sites were included in the data analysis. Recommended spray volumes for Roundup Biactive were between 100 and 250 l ha^{-1}. A few treatments were applied at less than 100 l ha^{-1}, in one case at 50 l ha^{-1} via a special low-volume (Danfoil) sprayer. This did not constitute a breach of the regulations but may have affected efficacy. Individual doses of 3 l ha^{-1} product were suggested for normal use, although in two cases 4 l ha^{-1} were applied. At these sites the maximum total dose of 6 l ha^{-1} was not exceeded.

On one conventional maize half-field the rate of atrazine application exceeded the maximum permitted, and at another site ioxynil, which is not approved in maize, was applied in a formulated mix with bromoxynil. The timings of weed control were somewhat variable with either the conventional or the GMHT herbicides sometimes applied late relative to the label recommendations. Late application of atrazine at one site was attributed to crop stress due to water logging. Early applications of glufosinate-ammonium were recorded and in some cases it was applied before the conventional herbicides. At one site, a conventional herbicide was applied to both the GMHT and the conventional crops to control volunteer oilseed rape (it was recommended for the GMHT half by the SCIMAC representative).

Table 1. Major herbicide AIs used (including repeat applications).
(National figures are hectares sprayed with the AI as percentages of the total crop area. FSE figures are the numbers of occasions on which each AI was applied to a field as percentages of the total number of fields grown of that crop. In each case, the use of chemicals in the FSEs matched national figures, on the basis of a Spearman's rank correlation test.)

herbicide AI	sprayed hectares (%)	FSE fields (%)
sugar beet (total crop area 172 566 ha, 40 FSE fields)[a]		
phenmedipham	266	228
ethofumesate	168	128
metamitron	134	120
desmedipham	85	35
triflusulfuron-methyl	76	53
lenacil	75	60
chloridazon	73	60
clopyralid	65	53
glyphosate	26	23
cycloxydim	20	5
		$s = 0.82$, $p = 0.003$
fodder beet (total crop area 10 481 ha, 26 FSE fields)[b]		
phenmedipham	151	162
metamitron	88	96
ethofumesate	86	92
chloridazon	36	81
desmedipham	27	38
clopyralid	18	42
lenacil	17	42
glyphosate	11	25
		$s = 0.93$, $p = 0.001$
forage maize (total crop area 109 413 ha, 68 FSE fields)[b]		
atrazine	100	94
bromoxynil	43	52
glyphosate	17	17
pyridate	11	2
pendimethalin	10	14
cyanazine	4	11
fluroxypyr	3	11
rimsulfuron	2	2
clopyralid	2	0
prosulfuron	0	15
simazine	0	6
		$s = 0.60$, $p = 0.049$
spring oilseed rape in England (total crop area 37 472 ha, 67 FSE fields)[a,c]		
glyphosate	58	66
trifluralin	37	36
metazachlor	17	28
clopyralid	16	31
diquat	11	7
fluazifop-P-butyl	10	6
paraquat	10	0
propaquizafop	9	10
propyzamide	7	0
benazolin	7	22
		$s = 0.75$, $p = 0.013$

[a] National average data from M. R. Thomas (personal communication).
[b] National average data from Garthwaite *et al.* (1999).
[c] Herbicide AI includes desiccant.

Spring oilseed rape, more than the other crops, appeared to have received herbicide applications after the label-recommended crop growth stage of 'post flower bud visible'. Conventional plots were treated after the label recommendation with propaquizafop (Falcon) on three sites and with fluazifop-P-butyl (Fusilade) on two sites. Liberty was applied to the GMHT side after the label recommendation on nine sites.

One conventional half-field was treated with metazachlor and quinmerac (Katamaran), which is not

Table 2. Mean ± s.e.m. numbers of applications of herbicides.
(Ranges for the FSE data are shown in parentheses; percentages of FSE sites for which conventional AI exceeded the national average are shown in square brackets; p is the probability for a test of FSE conventional versus FSE GMHT. Figures include pre-drilling applications and, for spring oilseed rape, desiccants.)

	sugar beet[a]	fodder beet[b]	forage maize[b]	spring rape[a]
fields not treated with herbicides (%)				
national average	0	1	1	21
FSE conventional	0 ± 3.0	0 ± 5.2	0	6 ± 3.0
FSE GMHT	3 ± 3.0	4 ± 5.2	0	3 ± 3.0
p	0.24	0.24	—	0.40
number of herbicide sprays				
national average	4.0	2.7	1.6	1.6
FSE conventional	3.65 ± 0.14	3.38 ± 0.20	1.32 ± 0.06	1.91 ± 0.07
	(1–6)	(1–6)	(1–3)	(0–4)
FSE GMHT	1.65 ± 0.14	1.50 ± 0.20	1.18 ± 0.06	1.69 ± 0.07
	(0–2)	(0–2)	(1–2)	(0–1)
p	< 0.001	< 0.001	0.097	0.023
number of AIs including repeat applications				
national average	10.2	5.2	2.1	1.9
FSE conventional	8.05 ± 0.36	7.00 ± 0.46	2.16 ± 0.10	2.18 ± 0.08
	(2–15)	(3–15)	(1–5)	(0–7)
FSE GMHT	1.95 ± 0.36	1.77 ± 0.46	1.32 ± 0.10	1.69 ± 0.08
	(0–4)	(0–3)	(0–2)	(0–3)
p	< 0.001	< 0.001	< 0.001	< 0.001
mean rate of AI (g ha^{-1}) on treated fields				
national average	2840	2579	1738	1445
FSE conventional	2551 ± 111	2495 ± 144	1684 ± 63	1376 ± 43
	(446–5859)	(922–5019)	(200–4288)	(0–3030)
	[32.5]	[46]	[38.2]	[39.7]
FSE GMHT	1637 ± 111	1484 ± 144	965 ± 63	1334 ± 43
	(0–3920)	(0–3150)	(598–1920)	(0–2780)
p	< 0.001	< 0.001	< 0.001	0.51

[a] National average data from M. R. Thomas (personal communication).
[b] National average data from Garthwaite *et al.* (1999).

permitted in spring oilseed rape. Another noteworthy occurrence, which was not outside the label recommendations, was a low-volume application (Airtec sprayer), which may have had implications for the herbicide efficacy. At another spring oilseed rape site the GMHT herbicide was applied with an adjuvant; this was not reported at any of the other sites. On another site, Liberty was applied to the GMHT oilseed rape 10 days before the conventional half was treated.

It is normal to apply some treatments to only part of a field. This occurred on three conventional spring oilseed rape sites. For calculation of the AI inputs, these were counted as being applied to the whole field. At one site, propaquizafop (Falcon) was applied only to the headland. At another site, benazolin and clopyralid (Benazalox) was applied as a spot treatment, and on the third site a pre-drilling treatment of glyphosate was applied in patches before the crop was sown. At another site, glyphosate was applied only to the conventional half of the field when the first crop failed and needed to be re-sown.

(d) *Comparison of herbicide input and weediness of fields*

Three main approaches to herbicide use have been followed by farmers in this experiment: post-emergence herbicides only; post-emergence herbicides and pre-emergence herbicides with residual activity; and GMHT herbicides. A fourth strategy using post-emergence herbicides and contact pre-emergence herbicides was recorded but was implemented at too few sites to be analysed.

To assess the effect of weediness on herbicide treatment, baseline seedbank densities and seedling counts were compared with the number of applications and the amount of AI used for each of these control strategies. Owing to the large number of conventional half-fields treated pre-emergence, few pre-treatment seedling counts were available from the conventional half-fields. Analysis had shown that, where pre-emergence herbicides were not used, seedbank densities and seedling counts did not differ between the conventional and GMHT half-fields (Heard *et al.* 2003*a*), and the pre-treatment seedling count from the GMHT half-field was used to represent the whole field. Regressions of baseline seedbank densities and seedling counts against herbicide use produced similar responses, and only the analyses for emerged seedlings are reported.

The relationship between herbicide use and seedling counts varied with crop. For beet (figure 4*a*,*b*) the regression lines for the three approaches were different. The uses of post-emergence herbicides alone and of

Table 3. Use of insecticides, nematicides, fungicides and molluscicides on FSE trial fields compared with national averages. (Average rate is that applied to treated fields only. Fungicide use includes sulphur.)

	sugar beet		fodder beet		forage maize		spring oilseed rape	
	FSE	national average[a]	FSE	national average[b]	FSE	national average[b]	FSE	national average[a]
insecticides and nematicides								
area treated (%)	30.0	22.7	34.6	29.8	0	6.9	76.1	54.1
mean number of spray rounds	0.4	0.3	0.5	0.4	0	0.1	1.3	1.0
average rate per field ($g\ AI\ ha^{-1}$)	505	346	425	385	0	1292	33	36
fungicides								
area treated (%)	47.5	40.2	7.7	9.6	0	0	7.4	29.2
mean number of spray rounds	0.5	0.4	0.1	0.1	0	0	0.1	0.5
average rate per field[a] ($g\ AI\ ha^{-1}$)	2493	2539	4147	3802	0	0	576	607
molluscicides								
area treated (%)	7.5	9.6	7.7	1.7	3.0	0.8	17.9	9.2
mean number of spray rounds	0.1	0.1	0.1	0.0	1.0	0.0	0.2	—
average rate per field ($g\ AI\ ha^{-1}$)	453	378	370	404	325	658	407	466

[a] National average data from M. R. Thomas (personal communication).
[b] National average data from Garthwaite *et al.* (1999).

GMHT herbicides varied positively with seedling densities, and the regression coefficient was greater for post-emergence herbicides than for GMHT herbicides. In the post-emergence strategy, up to four conventional post-emergence herbicide applications were made, whereas in the GMHT herbicide strategy the maximum dose of $6\ l\ ha^{-1}$ limited the number of applications to a maximum of two (figure 4*a*). Differences were the result either of the larger number of options available, or of poorer control when using conventional herbicides. Despite this, these regressions show that herbicide use increased in weedier fields. A similar picture was seen for the amount of AI applied (figure 4*b*), with maximums of $4039\ g\ ha^{-1}$ under the post-emergence strategy and $2160\ g\ ha^{-1}$ under the GMHT herbicide strategy. Herbicide use did not vary with weediness where pre- and post-emergence herbicides were applied and was greater than for the post-emergence or GMHT herbicide strategies, with a maximum of six applications and $4623\ g\ AI\ ha^{-1}$.

For maize, the regression analysis was different for the number of applications (figure 5*a*) and the amount of AI applied (figure 5*b*). The response of the number of applications to weediness was positive, and all three strategies could be represented by one line since in all cases the number of applications was either one or two. Analysis of the amounts of AI used produced three parallel lines showing greater AI use with the pre- and post-emergence strategy than with the post-emergence strategy, and the lowest AI use in the GMHT herbicide strategy. The amount of AI used was less responsive to weediness than in beet.

For spring oilseed rape (figure 6*a*,*b*), there was no response of herbicide use to weediness and, whereas there were different intercepts for the regression lines, the regression coefficients were the same for each herbicide strategy. Herbicides were usually applied once (figure 6*a*) and the intercepts for strategies based on post-emergence and GMHT herbicides were close to this value. All cases where three and four herbicides were used were employing the pre- and post-emergence strategy, and this increased the intercept to 1.5. At these sites, although the seedling counts were not exceptionally high, additional herbicide products were necessary to control problem weeds, such as thistles (*Cirsium arvense*) and wild oats (*Avena fatua*). The amount of AI used was greatest in the pre- and post-emergence strategy (figure 6*b*) and lowest in the post-emergence strategy, with a number of sites receiving no treatments. Use of GMHT herbicide was intermediate between these two strategies.

4. DISCUSSION

(a) *Site selection*

The site-selection process succeeded in choosing a diverse sample of sites to represent the main areas in England and Scotland growing these crops. Baseline seedbank data were viewed as an indicator of a site's potential weed flora and weed density, and is known to reflect previous management. Low-input farming results in more weed seeds in the soil (Squire *et al.* 2000). The distribution of the FSE seedbank samples fitted well with historical seedbank data from samples post-1960 (Squire *et*

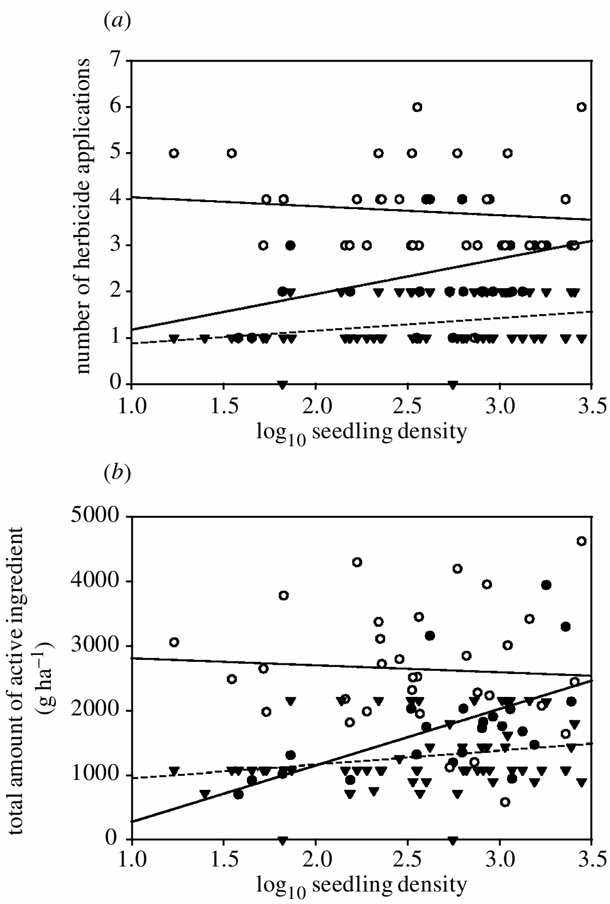

Figure 4. Effect of seedling emergence on (*a*) number of herbicide applications and (*b*) amount of herbicide used in beet. (*a*) The dependence of the number of herbicide applications for post-emergence herbicides alone (closed circles, solid line; $y = 0.404 + 0.771x$), pre- and post-emergence herbicides (open circles, dotted line; $y = 4.234 - 0.192x$) and GMHT herbicides (closed triangles, dashed line; $y = 0.604 + 0.276x$) on weed-seedling emergence measured on the GMHT half-field pre-treatment, using multiple linear regression. The best-fitting model was three separate lines (test for differences between slopes: $F_{2,117} = 3.09$, $p = 0.049$; overall regression: $F_{5,117} = 40.3$, $p < 0.001$). (*b*) The dependence of the amount of herbicide applied for post-emergence herbicides alone (closed circles, solid line; $y = -600 + 875x$), pre- and post-emergence herbicides (open circles, dotted line; $y = 2919 - 108x$) and GMHT herbicides (closed triangles, dashed line; $y = 686 + 230x$) on weed seedling emergence measured on the GMHT half-field pre-treatment, using multiple linear regression. The best-fitting model was three separate lines (test for differences between slopes: $F_{2,117} = 2.26$, $p = 0.014$; overall regression: $F_{5,117} = 20.1$, $p < 0.001$).

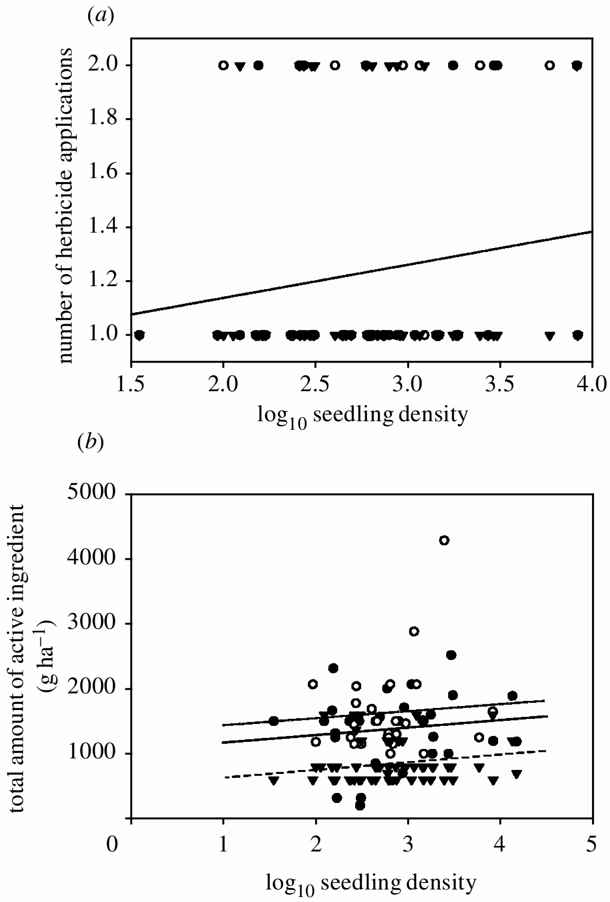

Figure 5. Effect of seedling emergence on (*a*) the number of herbicide applications and (*b*) the amount of herbicide used in maize. (*a*) The dependence of the number of herbicide applications for post-emergence herbicides alone (closed circles), pre- and post-emergence herbicides (open circles) and GMHT herbicides (closed triangles) on weed seedling emergence measured on the GMHT half-field pre-treatment, using multiple linear regression. The best-fitting model was a single line: $y = 0.892 + 0.123x$ (test for differences between slopes: $F_{2,107} = 0.84$, $p = 0.435$; test for differences between intercepts: $F_{2,107} = 1.71$, $p = 0.185$; overall regression: $F_{1,111} = 2.86$, $p = 0.094$). (*b*) The dependence of the amount of herbicide applied for post-emergence herbicides alone (closed circles, solid line; $y = 1057 + 115x$), pre- and post-emergence herbicides (open circles, dotted line; $y = 1322 + 115x$) and GMHT herbicides (closed triangles, dashed line; $y = 514 + 115x$) on weed seedling emergence measured on the GMHT half-field pre-treatment, using multiple linear regression. The best-fitting model was three parallel lines (test for differences between slopes: $F_{2,107} = 0.80$, $p = 0.453$; test for differences between intercepts: $F_{2,107} = 28.0$, $p < 0.001$; overall regression: $F_{3,109} = 19.4$, $p < 0.001$).

al. 2003), after the widespread adoption of herbicides, validating the selection.

The selection process aimed to favour low-intensity farms, since these are thought to be more important for wildlife. Low-intensity farms are relatively infrequent, because many produce low yields and are consequently uneconomic. Most farms in the selection were of medium to high intensity. When preparing the questionnaire, it had been proposed that higher yields might represent a greater intensity of farming (e.g. higher chemical inputs or better timed farming operations) and these sites might have lower seedbanks. This was not the case, and there was no direct relationship between winter wheat yield and farming intensity. However, a selection of only low-intensity farms would have resulted in only high weed seedbanks and not the range of seedbank densities necessary to test the null hypothesis, whereas high-intensity farms were found to have both high and low seedbanks. The occurrence of high seedbanks on high-intensity farms may be caused by over-reliance on herbicides at the expense of other weed-control measures, such as good crop rotation or the

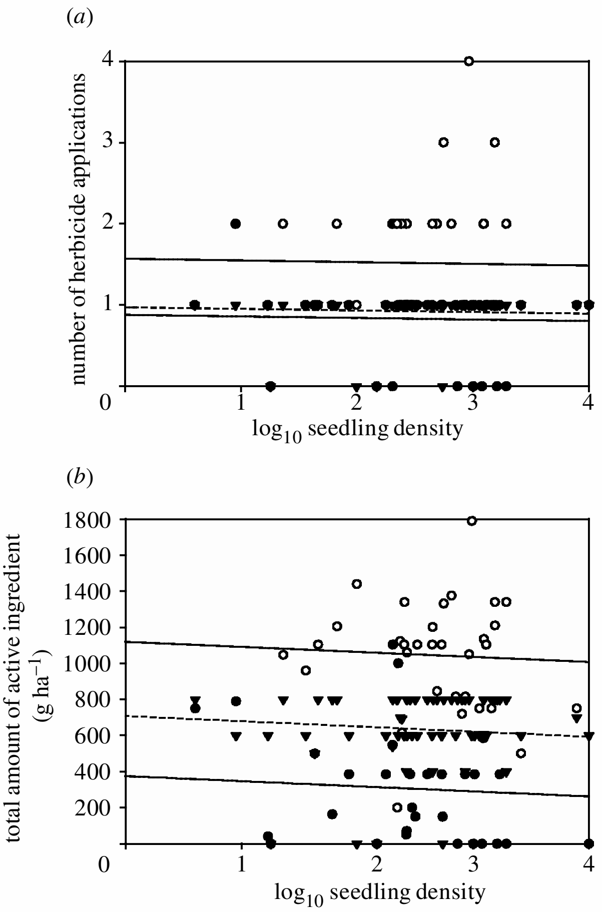

Figure 6. Effect of seedling emergence on (*a*) the number of herbicide applications and (*b*) the amount of herbicide used in spring oilseed rape. (*a*) The dependence of the number of herbicide applications for post-emergence herbicides alone (closed circles, solid line; $y = 0.879 - 0.019x$), pre- and post-emergence herbicides (open circles, dotted line; $y = 1.566 - 0.019x$) and GMHT herbicides (closed triangles, dashed line; $y = 0.973 - 0.019x$) on weed seedling emergence measured on the GMHT half-field pre-treatment, using multiple linear regression. The best-fitting model was three parallel lines (test for differences between slopes: $F_{2,123} = 0.99$, $p = 0.374$; test for differences between intercepts: $F_{2,123} = 18.1$, $p < 0.001$; overall regression: $F_{3,125} = 12.1$, $p < 0.001$). (*b*) The dependence of the amount of herbicide applied for post-emergence herbicides alone (closed circles, solid line; $y = 375 - 28.3x$) pre- and post-emergence herbicides (open circles, dotted line; $y = 1120 - 28.3x$) and GMHT herbicides (closed triangles, dashed line; $y = 705 - 28.3x$) on weed seedling emergence measured on the GMHT half-field pre-treatment, using multiple linear regression. The best-fitting model was three parallel lines (test for differences between slopes: $F_{2,123} = 2.44$, $p = 0.091$; test for differences between intercepts: $F_{2,123} = 62.8$, $p < 0.001$; overall regression: $F_{3,125} = 41.1$, $p < 0.001$).

use of inversion tillage. Within the selection, cropping-intensity scores of 0–2 and low-to-average wheat yields of 6–8 tonnes ha^{-1} were seen on 10–20% of beet and spring oilseed rape sites chosen, suggesting some success in including less intensive sites. No data are available on the proportion of weedy sites found in the UK today.

(b) *Crop management*

Crop management was in line with current practice in terms of sowing dates, choice of cultivar and non-herbicide inputs. Slight delays in sowing in 2000 (for administrative and legal reasons) and 2001 (owing to wet weather) were still well within the normal range.

During 2002, some seed lots of the GMHT spring oilseed rape hybrid PH96S-452 were discovered by Aventis to be contaminated with 2.8% seed containing an unauthorized genetic modification not covered by their release consent. These seed lots had been planted on 12 sites in England and two in Scotland. The modification was for antibiotic resistance and had previously been assessed as not posing a risk to human health (Advisory Committee on Releases to the Environment 2002). Since this did not affect the objective of these evaluations, and the crops were near harvest, these sites were allowed to continue until harvest when the seed was disposed of following the normal GMHT procedures (Defra 2002*c*).

(c) *Audit of inputs*

The audit process was initiated to assess all inputs carefully, to determine whether they were appropriate and to check for bias. Concern had been expressed at the outset that it might be possible for farmers or SCIMAC to distort the results by using inappropriate management on one or both halves of the field. SCIMAC advice on the growth of the GMHT crops was necessary since the farmers were unfamiliar with growing them, and the strategies for the provision of that advice varied between the two companies who owned the crops. For beet, representatives of Monsanto tutored the farmers' advisers on the use of the GMHT technology, and the agronomist made the final recommendation using the simulated label as a guide. For maize and spring oilseed rape, the farmer or adviser made the final recommendation in direct association with representatives of Aventis (now BayerCropScience).

The types of AIs used, the numbers of applications and the amounts of AI used on crops across the FSEs were consistent with current commercial practice as recorded in the national pesticide-usage surveys in the vast majority of cases (Garthwaite & Thomas 1999; Garthwaite *et al.* 1999). It is necessary to be cautious when comparing data collected over three years with average national data collected in one year since variation in the need for inputs can occur for a variety of reasons. Lower herbicide use may be related to late sowing in 2000 and 2001. Late sowing tends to reduce weed emergence (Champion *et al.* 1995), and the higher temperatures can encourage crop growth (Houghton & Thomas 1996), making it more competitive. Wet weather during the growing season can improve the efficacy of some herbicides through improved uptake. Whilst there was no evidence of bias in conventional or GMHT inputs, it appeared that the different strategies used by the two companies for recommendations for GMHT herbicide inputs resulted in inputs to beet being applied more flexibly than those to spring oilseed rape or maize.

Fodder beet was over-sampled relative to sugar beet because it is a less intensive crop. Herbicide inputs in the FSE fodder beet were lower than in sugar beet, but with a smaller difference than expected; compared with national figures, the FSE conventional fodder beet received higher herbicide inputs. Covariate analyses conducted on various protocols failed to find an effect of crop type in beet, confirming that they do form a continuum, with fodder beet being the less intensive crop. Out of the fodder beet growers in this study, 19% also grow sugar beet, and this may have had an effect on the way that the crops were managed. Compared with 1997 survey data, despite the use of more sprays, less AI was used. This may reflect registrations of new low-weight AIs for use in fodder beet since the last survey.

Although herbicide applications to spring oilseed rape were appropriate, several took place later than the recommended application time. For the audit, interpolation of spring oilseed rape crop-growth stage on the day of spraying is difficult from the crop data available. First, crop-growth assessments were carried out every 14 days or so, whilst, at flowering, spring oilseed rape development is rapid. Second, at one spring oilseed rape site re-drilling occurred, and consequently the field was patchy, with survivors from the original crop. Analyses were checked to ascertain the possible effect of late application. Applications that may have been late were tested using a covariate analysis. In general, the effect of this covariate was negligible, except for the analysis of final counts of dicotyledonous weeds. When this response variable was re-analysed, leaving out any site for which application was outside the label recommendations, there was no difference in the overall conclusions, the estimated treatment effect for the full set of sites being $R = 0.64$, $p = 0.002$ and that for the reduced set being $R = 0.76$, $p = 0.018$. We concluded that the possible lateness of application did not, in any event, alter the findings reported by Heard *et al.* (2003*a*), and so no further action was necessary.

The greatest difference between the conventional and the GMHT systems was the application timings of the herbicides. In all crops, usually only one or two GMHT applications were made compared with two conventional applications in maize and spring oilseed rape and up to six applications in beet. Pre-emergence conventional herbicides were used in *ca.* 50% of sites in each crop. This prevented the early build-up of weeds on the conventional half-fields (figure 2*a–c*) compared with the untreated GMHT half-fields. However, despite the use of pre-emergence herbicide on 50% of sites, the majority of this was the relatively weak herbicide trifluralin, and early weed cover was greater on the conventional half-fields in spring oilseed rape than in the GMHT half-fields. A similar effect was noted with seedling counts and is covered in Heard *et al.* (2003*a*). The speeds of reduction in weed cover following the GMHT herbicide applications differed owing to differences in mode of action. Glyphosate is translocated and slow-acting, and weeds did not appear to re-grow, whereas glufosinate-ammonium is quick-acting but has contact activity only and some weeds recovered.

(d) *Comparison of FSE inputs with those of other trials*

Other trials have included comparisons of conventional weed-control programmes with those used in GMHT crops. In beet in the UK, a typical conventional programme consisting of a pre-emergence and four post-emergence applications was comparable with glyphosate treatments totalling 6 l ha^{-1} (Tenning 1998). The amount of glyphosate AI applied was 52% of that used in the conventional system. In German variety trials, control of heavy weed infestations was achieved with two to three doses of glyphosate at rates of 2–3 l ha^{-1} beginning at the two-to-four-leaf stage of the crop (Platte *et. al* 1998). In the FSEs, conventional beet crops were usually sprayed four times with seven or eight AIs, and the GMHT crops were sprayed on average twice with glyphosate at 3 l ha^{-1}, which is 64% of the AI applied to the conventional crops. In the USA, where GMHT sugar beet is not grown commercially, commercial conventional crops receive up to 11 herbicide applications (including repeats) per unit area, at an average rate of 1 kg AI ha^{-1}. Predicted herbicide use in glyphosate-tolerant sugar beet would be two applications using a total of 1.7 kg AI ha^{-1}, an increase of 70% over conventional herbicides (Gianessi *et al.* 2002*a*). A recently published study by the same authors has examined the situation that is likely to occur in Europe. Citing work by other authors, they report an estimated reduction in AI use to 60% of that currently used (Gianessi *et al.* 2003), the difference being caused by the current relatively low herbicide use in conventional sugar beet in the USA.

Commercial genetically modified maize is grown in the USA, although herbicide tolerance is a much less favoured trait than insect resistance. GMHT maize is estimated to have been grown on 2.3 million ha (8% of the corn area) in 2001 (Gianessi *et al.* 2002*b*), with 60% of this being Roundup Ready (glyphosate tolerant). Adoption of GMHT maize in the USA has been driven by the improved control of certain troublesome species. Wider adoption is reported to have been limited by the current lack of favoured cultivars with the required modification, and adoption is notably lower in states that have large export markets in Europe. University research in the USA found that the weed control in GMHT maize from single applications of glyphosate or glufosinate-ammonium was inadequate, and recommended strategies now involve either the use of two glyphosate or glufosinate-ammonium sprays or the use of a pre-emergence conventional herbicide followed by one post-emergence glyphosate or glufosinate-ammonium spray (Gianessi *et al.* 2002*b*). It is estimated that, for the glufosinate-ammonium programme, this represents an average reduction of 1.2 kg AI ha^{-1} (36%) compared with conventional strategies. In FSE GMHT maize, most fields received one application of herbicide at rates averaging 3.5 l product ha^{-1}, representing a reduction of 57% compared with conventional herbicide use.

In spring oilseed rape, trials work in the UK has found good weed control with single applications of 2, 3 and 4 l ha^{-1} glufosinate-ammonium (Read & Ball 1999), the higher rates being necessary where species less susceptible to the herbicide, such as *Lamium purpureum* or *Fumaria officinalis*, were present. Trials work in Germany has investigated the possibility of applying herbicides to GMHT oilseed rape using weed thresholds (spraying only when weed densities reach a certain threshold), a system that is not possible with residual pre-emergence herbicides. The conclusion was that glufosinate-ammonium is suitable for this approach owing to the flexibility in its timing of application (Garbe & Sauermann 2000). In the USA, the vast majority (81%) of canola is grown in North Dakota

(Gianessi *et al.* 2002*c*). It is sown in spring and weeds are the most limiting factor. In North Dakota, 70% of the area grew transgenic canola in 2001, 5% of which was tolerant to glufosinate-ammonium (Gianessi *et al.* 2002*c*). Average application rates of glufosinate-ammonium represent a reduction in AI of 40% compared with conventional herbicides. In the FSEs, GMHT spring oilseed rape crops were usually sprayed once with an average rate of 3.5 l product ha^{-1} so that the amount of AI used was not significantly different from that used on conventional spring oilseed rape.

The system of GMHT crop management studied in the FSEs represents only one possible option and this may change with increased familiarity with the crops. The discussion above illustrates that production systems using GMHT crops may develop after introduction and that the eventual method of use will be guided by the situations found in each country. Other research work has examined other ways that this technology could be used (Dewar *et al.* 2003), but these methods are not considered in the FSEs.

(e) *Yields*

Crop yields were not routinely recorded from the FSE sites. Yields can be variable within fields, and differences in yield potential between conventional crop cultivars can be greater than those seen between conventional and GMHT crop cultivars. Since these evaluations were not intended to compare the performances of the crops but rather the effects on biodiversity of the management of the crops, yields are not necessary to test the null hypothesis. Crop-assessment data has shown that there was little difference between the development of the conventional and the GMHT crops in terms of height (maize and spring oilseed rape) or crop cover (beet).

Farmers' estimates of yields were gathered, where available, but in many cases these were not adequate for analysis. In GMHT beet, harvesting procedures were altered (more crown was left on the harvested roots) to reduce the likelihood of volunteer GMHT beet re-growing in the fields, making these yield estimates unreliable. Recently published work (Dewar *et al.* 2003) has modelled yield reductions in GMHT beet resulting from delayed herbicide application. Comparison of average delays in the FSEs with these models suggests that the FSE sites were generally treated 10–14 days earlier than the timings in the published study where yield loss occurred. It is unlikely that yields were reduced by the timings of GMHT herbicide application used in this study.

(f) *Herbicide use in relation to weediness*

Regression analysis was used to compare herbicide applications with the need for weed control (seedling densities) based on the weed-control strategy used by the farmer. Herbicide-application systems that have only a few weed-control possibilities (maize and spring oilseed rape) were generally unresponsive to weed densities. However, multiple-application systems (beet) have more scope and, where pre-emergence strategies were not used, were responsive to weed pressure. Systems using pre-emergence herbicides are used as an insurance strategy.

(g) *Conclusions*

The wide range of situations studied at these sites allows the comparison of the management systems of the conventional and the GMHT crops to be undertaken under realistic conditions. The involvement of farmers and their advisers has been invaluable in achieving this. Herbicide use differed greatly between the conventional and the GMHT crops. The audit of inputs found no evidence of bias in the application of inputs. The sites studied in this evaluation represent the range of situations, management scenarios and levels of inputs currently used and are therefore a microcosm of current commercial and putative GMHT practice (if the current draft label recommendations are adopted).

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GLOSSARY

AEA: Administrative Experimental Approval
AI: active ingredient
FSE: Farm Scale Evaluation
GMHT: genetically modified herbicide tolerant
NIAB: National Institute of Agricultural Botany
NL: National List
PSD: Pesticide Safety Directorate
SCIMAC: Supply Chain Initiative for Modified Agricultural Crops

Visit http://www.pubs.royalsoc.ac.uk to see an electronic appendix to this paper.